Internal Waves in the Vicinity of the Kuroshio Path

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LONG-TERM GOALS

My long-term scientific goals are to understand the dynamics of small-scale processes and to quantify the mechanisms by which mixing occurs in the ocean and thereby help develop improved parameterizations of mixing for ocean models. Mixing within the stratified ocean is a particular focus as the complex interplay of internal waves from a variety of sources and turbulence makes this a current locus of uncertainty. A better understanding of energy sources and the dynamics of internal waves will help improve a physics-based parameterization scheme for ocean models.

OBJECTIVES

For this project, our broad focus is on inertial waves, internal tides, internal wave continuum, and nonlinear internal waves in a complex and diverse dynamic environment (Fig. 1) where the Kuroshio interacts with the shallow and the deep topography (Tang et al., 2003), strong nonlinear internal waves and finescale inertial shear layers are observed (Rainville and Pinkel, 2004), and strong internal tides have been suggested by numerical models (Niwa and Hibiya, 2004). Primary objectives of this project are 1) to provide a geographical map and the long-term variation of internal wave energy and shear variances, 2) to quantify high-frequency nonlinear internal wave energy, and 3) to quantify energy and shear of inertial waves along the Kuroshio path.

APPROACH

We will analyze observations taken in the vicinity of the Kuroshio Path from the Luzon Strait to the southern East China Sea. Available data sets include 1) moored and bottom mounted ADCPs, and shipboard ADCP observations, 2) CTD profiles, 3) moored temperature, 4) moored current meter data, and 5) echo sounder data. Previous studies of these data focused primarily on sub-inertial processes. Most of available data were taken at a sampling rate of < 60 minutes, suitable for studying internal waves.

WORK COMPLETED

In last year, most of my effort supported under this project was to supervise a graduate student. A preliminary analysis of historical CTD data was performed to quantify the seasonal variations of the Kuroshio front in the Luzon Strait and along the east coast of Taiwan.

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RESULTS

The water mass east of the Philippine is often defined as the Kuroshio water (black block in Fig. 2), and the water mass west of the Philippine is often defined as the South China Sea water (red block in Fig. 2) (Chern and Wang, 1998). Within the Kuroshio along the east coast of Taiwan, both types of water have been observed (Fig. 3). It is unclear where and how these two water masses mix. Within the Luzon Strait, the Kuroshio, barotropic tides, baroclinic tides, and other oceanic processes interacting with submarine ridges are likely the potential sources for the turbulence mixing (Fig. 2).

Averaged density fields across the Kuroshio along the east coast of Taiwan in summer and in winter are constructed using historical CTD data collected by the National Center for Ocean Research (NCOR) between 1985 and 2002 (Figs. 4 and 5). The isopycnal tilts associated with the Kuroshio and the boundary countercurrent along the east coast of Taiwan are revealed. Similar temperature and salinity fields are constructed, as well as fields of their standard deviations (not shown). We are in the process of quantifying the seasonal and geographical variations.

IMPACT/APPLICATION

The mass, heat, momentum, and energy transports of the Kuroshio are potentially important for modulating Asian waters. To improve our skill of modeling turbulent processes and quantifying turbulence mixing within the Kuroshio and between the Kuroshio and surrounding water, we need to identify energy sources of internal wave and turbulence mixing along the Kuroshio path. Results of the present analysis of historical data will provide the spatial and temporal distributions of internal wave energy and shear variances along the path of the Kuroshio and improve our understanding of the Kuroshio dynamics.

REFERENCES

Chern, C.-S., J. Wang, The spreading of the South China Sea water to the east of Taiwan during summertime, *Acta Ocean.. Taiwanica*, **36**, 97-109, 1998.

Liang, W. D., T. Y. Tang, Y. J. Yang, M. T. Ko and W. -S. Chuang, Upper-ocean currents around Taiwan, *Deep Sea Res*., **40**, 1085-1105, 2003.

Niwa, Y. and T. Hibiya, Three-dimensional numerical simulation of the M2 internal tides in the East China Sea, *J. Geophys. Res., 109, C04027,* doi:10.1029/2003JC001923, 2004.

Rainville, L., and R. Pinkel, Observations of energetic high-wavenumber internal waves in the Kuroshio, *J. Phys. Oceanogr.*, **34**, 1495-1505, 2004.

Tang, T. Y., H. Y. Tai, and Y. J. Yang, The flow pattern north of Taiwan and the migration of the Kuroshio, *Cont. Shelf Res*., **20**, 349—371, 2003.

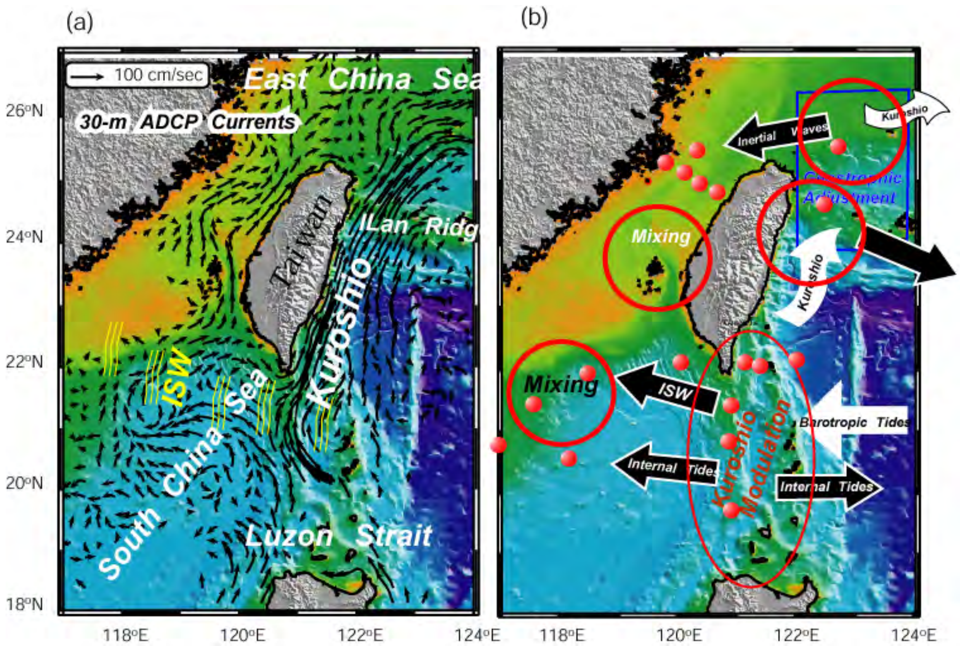

Figure 1: (a) Topography of western Pacific near Taiwan. Composite shipboard ADCP velocity at 30-m depth (figure adopted from Liang et al. 2003) shows Kuroshio crossing regions of strong topography in Luzon Strait and impinging on the continental shelf of the East China Sea northeast of Taiwan. (b) Potential small-scale processes in the region. Potential hot spots for generation of internal waves and turbulence mixing are red circled in (b). Red bullets mark positions of available mooring data for the present analysis.

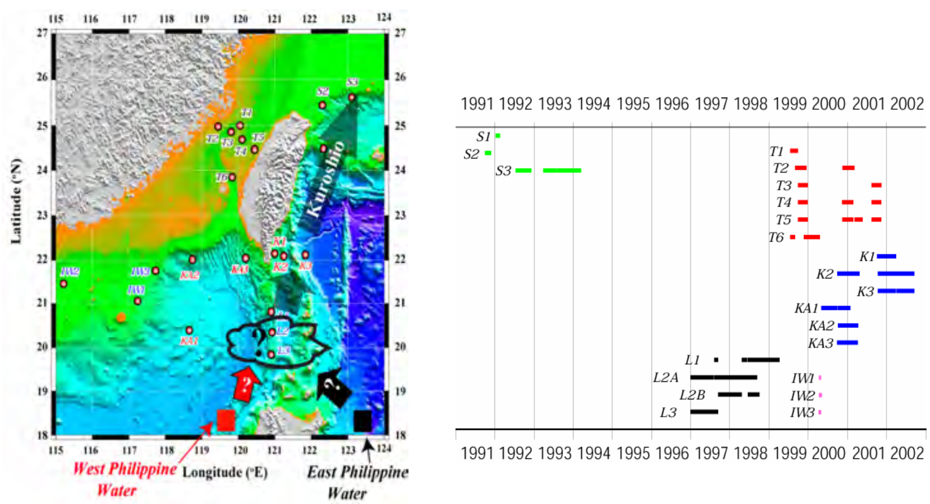

Figure 2: Positions (left panel) and periods (right panel) of moored ADCPs and current meters in ECS, Taiwan Strait, Kuroshio, Luzon Strait, and SCS. Stations of current meter and ADCP moorings are labeled. Red and Black blocks represent the area where water masses are commonly defined as South China Sea Water and Kuroshio Water, respectively. We emphasize in our analysis that this definition is misleading and term them as west Philippine water and east Philippine water, respectively. In the main axis of the Kuroshio, e.g. station K2, the water mass is a mixture of these two water types.

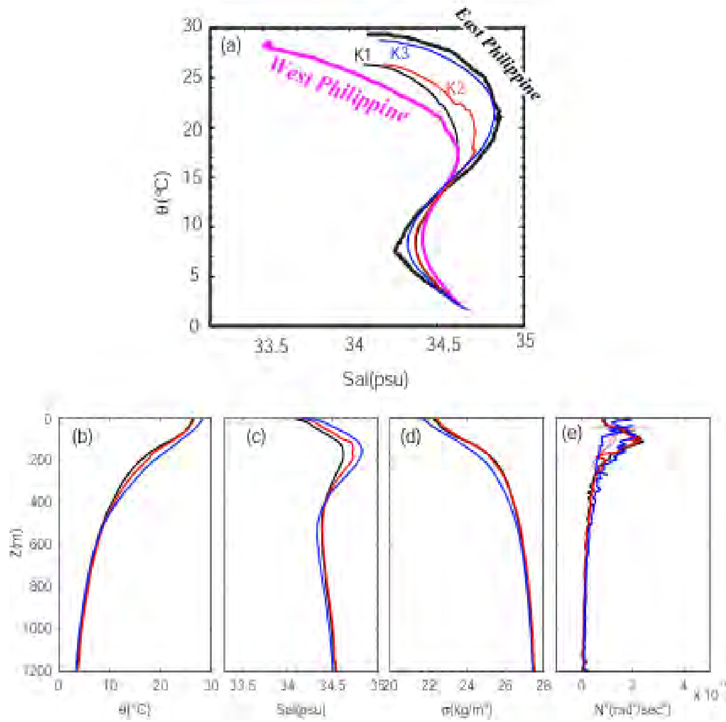

Figure 3: Water properties at three mooring positions, K1 (black), K2 (red), and K3 (blue). The panel (a) shows T-S properties of water masses at mooring stations, west of Philippine (magenta), and east of Philippine (thick black). Vertical profiles of potential temperature, salinity, potential density, and N^2 are shown in panels (b), (c), (d), and (e).Thin curves in panel (e) are total shear squared computed from mooring ADCP data.

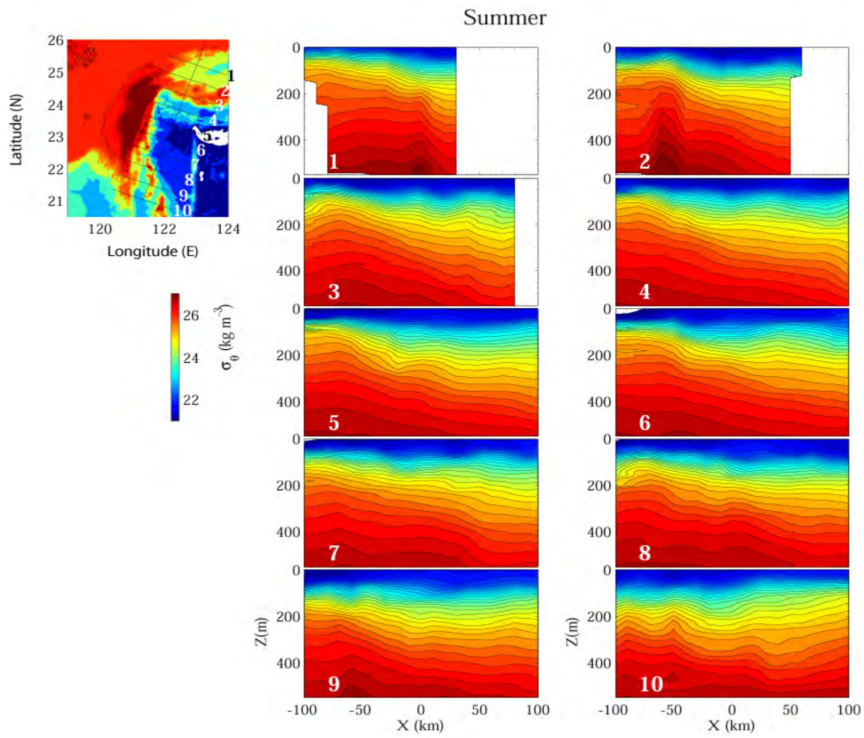

Figure 4: Average density fields in summer across the Kuroshio along the east coast of Taiwan constructed using historical CTD data.

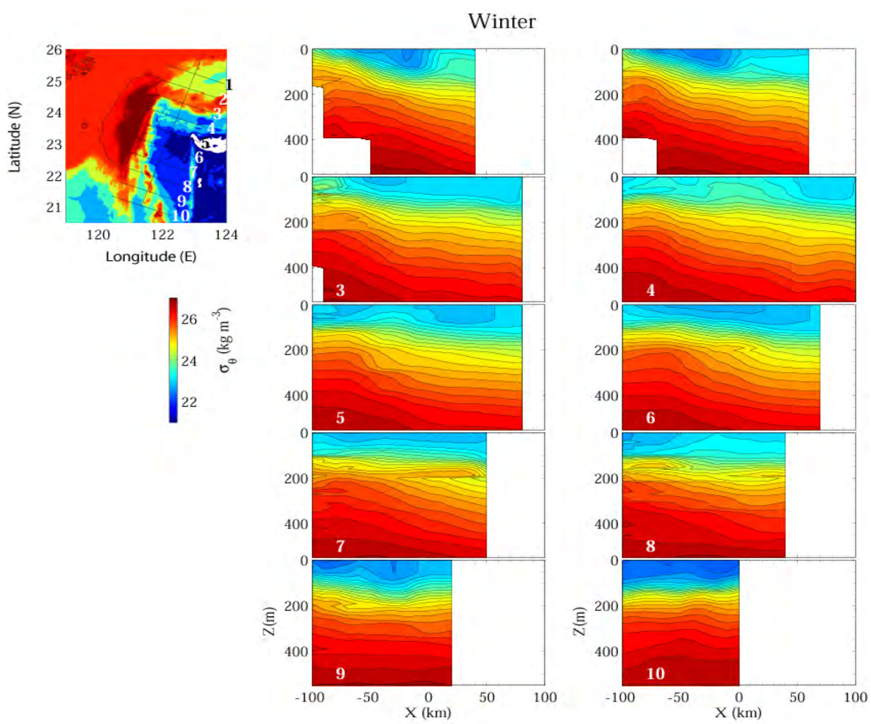

Figure 5: Average density fields in winter across the Kuroshio along the east coast of Taiwan constructed using historical CTD data.